Intergalactic Magnetic Fields from Quasar Outflows

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Abstract. Outflows from quasars inevitably pollute the intergalactic medium (IGM) with magnetic fields. The short-lived activity of a quasar leaves behind an expanding magnetized bubble in the IGM. We model the expansion of the remnant quasar bubbles and calculate their distribution as a function magnetic field strength at different redshifts. We find that by a redshift $z \sim 3$, about 5–80% of the IGM volume is filled by magnetic fields with an energy density $> 10\%$ of the mean thermal energy density of a photo-ionized IGM (at $\sim 10^4$ K). As massive galaxies and X-ray clusters condense out of the magnetized IGM, the adiabatic compression of the magnetic field could result in the fields observed in these systems without a need for further dynamo amplification.

1 Introduction

Clusters of galaxies contain substantial magnetic fields with strengths $B \sim 0.1 - 10\ \mu$G and coherence lengths $\ell \sim 10$ kpc [1]. The origin of such fields could have important implications for structure formation. Assuming flux conservation, a cluster field $B_{\rm cl} \sim 10^{-7}$ G would imply $B_{\rm IGM} \sim 10^{-9}$ G in the diffuse intergalactic medium (IGM), which would constitute $\sim 5\%$ of the thermal energy density of a photoionized IGM. The observational constraints on an intergalactic magnetic field (IGMF) are weak, requiring only that $B_{\rm IGM} < 10^{-8}(\ell/\ {\rm Mpc})^{-1/2}$ G in the currently popular ΛCDM model [1].

Unfortunately, there is no convincing model for the formation of cluster fields or the IGMF. Because the rotation times of clusters exceed the Hubble time, dynamos are expected to be ineffective. Primordial generation scenarios cannot explain the large coherence lengths [2]. Models that generate magnetic fields during structure formation [3] or in starbursts [4] suffer from similar problems.

We have examined the possibility that the IGMF was originally produced near supermassive black holes and expelled into the IGM through mechanical outflows [5] from radio-loud quasars (RLQs) and broad absorption line quasars (BALQs). Supermassive black holes are one of the few classes of astrophysical objects with energy reservoirs large enough to account for the large-scale fields in clusters, and the relatively small number of powerful sources can accomodate the large observed coherence lengths, as emphasized by [6]. For more details on the model, see [7].

2 Filling Factor of Magnetized Regions & Mean Fields

While a quasar is active, its outflow is in the form of twin collimated jets (for a RLQ) or equatorial winds (for a BALQ). After the quasar becomes dormant, the outflow remnant is overpressured with respect to the IGM and continues to expand in comoving coordinates until its outward velocity matches the Hubble flow velocity. We assume that the outflow remnant isotropizes and expands adiabatically as a spherical shell during this late phase.

Simple energy conservation provides a surprisingly accurate estimate of the final comoving bubble size $\hat{R}_{\rm max}$. Balancing the energy input of the quasar and the final kinetic energy of the shell, we find that $\hat{R}_{\rm max} \propto [L_q \tau_q \varepsilon_K (1+\varepsilon_B)]^{1/5}$, where L_q is the luminosity of the quasar, τ_q is its lifetime, ε_K is the ratio of the mechanical and radiative luminosities, and ε_B is the ratio of the magnetic and mechanical energy outputs. Note the weak dependence on the quasar parameters, making our results robust to uncertainties in their measurement. In particular, we find that magnetic fields do not play an important role in the expansion for realistic values of ε_B. We therefore ignore the geometric and magnetohydrodynamic effects of the magnetic field and assume simple flux conservation.

We next calculate the number of quasar sources. For $z < 4$, we use the observed optical luminosity function of quasars [8] together with an assumed incidence rate of outflows f. For $z > 4$, we assume that the incidence rate of quasars is proportional to the Press-Schechter mass function, with the proportionality constant set by matching to the observed luminosity function at $z \sim 4$ [9].

We examine two quasar models: the RLQ model, with $\varepsilon_B = 0.1$ and $f = 0.1$ [10], and the BAL model, with $\varepsilon_B = 0.01$ and $f = 1$ [11]. Note that there are no existing observations of magnetic fields in BALQs, though the fields may play an important role in the wind mechanism [12].

We then calculate the total filling factor of the quasar bubbles as a function of redshift, $F(z)$, and the global volume-averaged magnetic energy density, $\bar{u}_B(z)$, for our two models by numerically integrating the equation of motion of each remnant and summing over all quasar sources. Our results are shown in Fig. 1, along with the distribution of magnetic field strengths for a series of redshifts.

3 Results

We predict a cellular IGMF filling a substantial fraction of space by $z \sim 3$ (Fig. 1), with each cell a fossil bubble produced by a single magnetized quasar outflow. Cells generated by RLQ quasars are more highly magnetized than those from BAL quasars but fill a smaller volume. We predict that $B_{\rm IGM} \sim 10 f \varepsilon_B$ nG when averaged over all of space; for each of our models, simple adiabatic compression of such an IGMF can account for the observed cluster magnetic fields.

Direct detection of the cells via Faraday rotation measurements will be difficult, but electron acceleration by shocks in the cells will cause synchrotron emission. The same accelerated electrons produce γ-rays through inverse-Compton scattering of the cosmic microwave background. Correlated maps of the γ-ray and radio skies may allow us to calibrate the magnetic field in the shocks [13].

Finally, we note that the non-thermal pressure of the magnetic fields may help to resolve the discrepancy between simulated and observed line widths in the Lyα forest [14].

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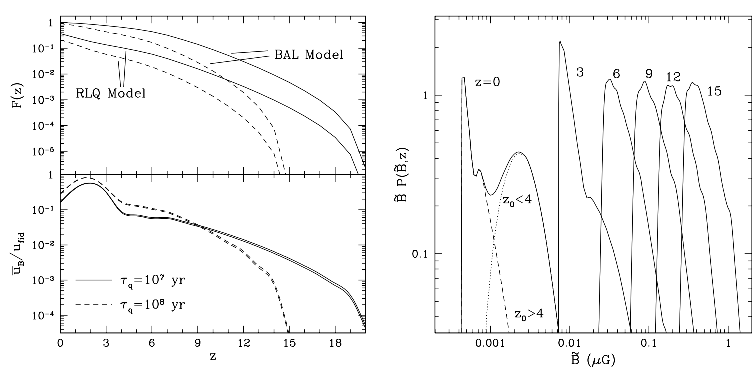

Fig. 1. *Top Left:* Volume filling fraction of magnetized bubbles $F(z)$. *Bottom Left:* Ratio of magnetic energy density, $\bar{u}_B$, to the fiducial thermal energy density $u_{fid} = 3n(z)kT_{IGM}$, where $T_{IGM} = 10^4$ K. In each of these panels, results are shown for both the RLQ and BALQ models. *Right:* Probability distributions of bubble magnetic field, $P(\tilde{B}, z)$, for the RLQ model, at various redshifts. Here $\tilde{B} = B/(\sqrt{\epsilon_B/0.1})$; in these units the curves are independent of ϵ_B. The dotted curve shows the contribution to the $z = 0$ distribution function from quasars forming at $z_0 < 4$ and the dashed curve shows the contribution from quasars at $z_0 > 4$. All curves are normalized to have unit area.